

Composites Damage Tolerance Workshop
October 23 – 24, 2006
Abstract

The Composite Damage Tolerance Workshop included participants from NASA, academia, and private industry. The objectives of the workshop were to begin dialogue in order to establish a working group within the Agency, create awareness of damage tolerance requirements for Constellation, and discuss potential composite hardware for the Crew Launch Vehicle (CLV) Upper Stage (US) and Crew Module. It was proposed that a composites damage tolerance working group be created that acts within the framework of the existing NASA Fracture Control Methodology Panel. The working group charter would be to identify damage tolerance gaps and obstacles for implementation of composite structures into manned space flight systems and to develop strategies and recommendations to overcome these obstacles.



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

WELCOME!

Workshop Objectives

- Begin dialogue to establish a working group within the Agency
 - Act within framework of the NASA Fracture Control Methodology Panel
 - Fracture Panel Charter – Develop requirements and implementation methodologies and procedures for fracture control of NASA manned space flight systems
 - Proposed Working Group Charter – Identify damage tolerance gaps and obstacles for implementation of composite structures into manned space flight systems; Develop strategies and recommendations to overcome these obstacles
- Create awareness of composite DT requirements for Constellation
 - General Fracture Control – NASA-STD-5019
 - Fracture Control of Composites – MSFC-RQMT-3479
 - Imposed by 5019
- Discuss potential composite hardware for CLV Upper Stage (US) and Crew Module



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

What is damage tolerance? Mil-HDBK-17-3F, paraphrased

- Ability of a structure to sustain design loads in the presence of damage until the damage is detected, either through inspection or malfunction, and repaired (or replaced)
 - Damage Type? – For composites this includes delaminations, cuts, scratches, gouges, fiber breakage, porosity, microcracking, etc...
 - Damage Cause? – Fatigue, corrosion, environmental effects, accidental events, manufacturing, etc...

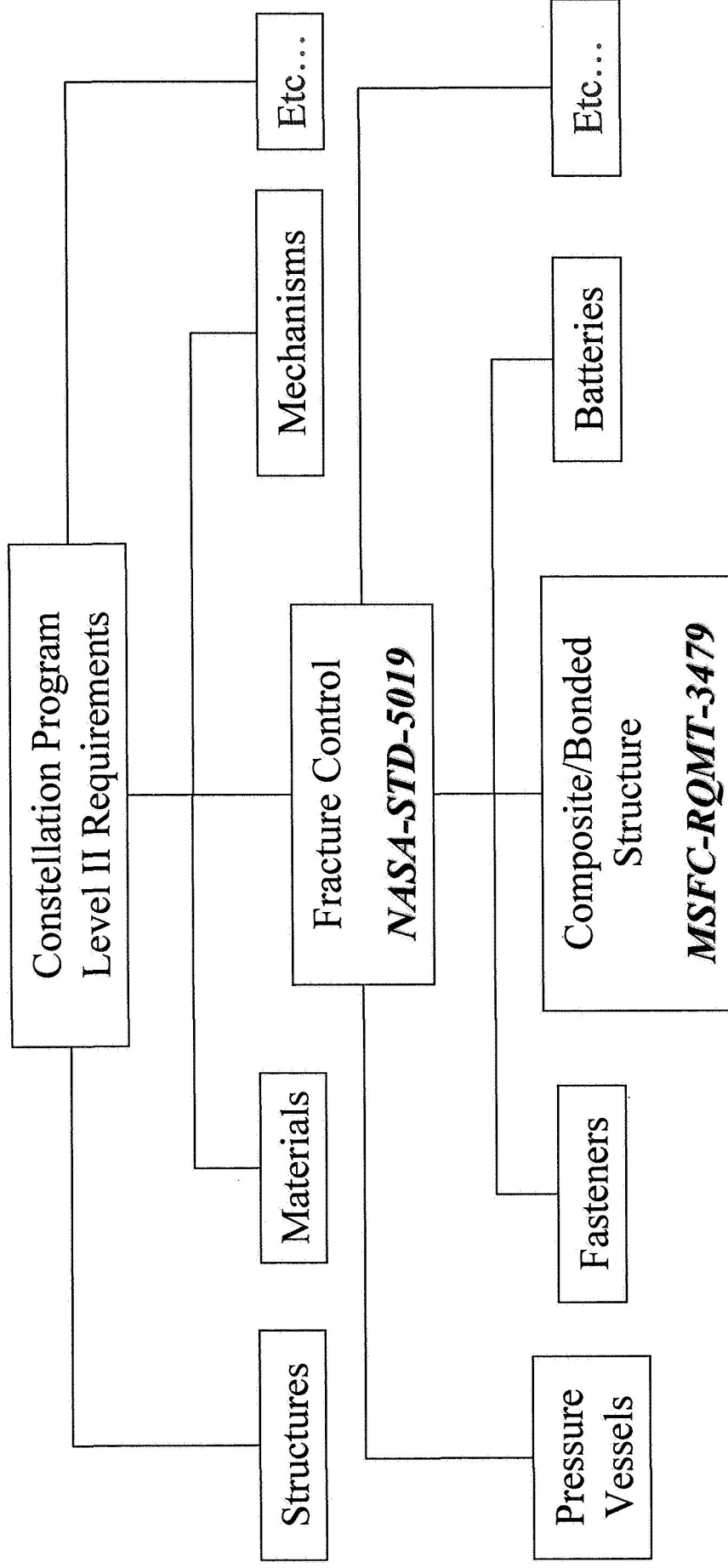
Damage tolerance of composites has an integrated role with different aspects of composite structural assessment & test, design, manufacturing, material characterization, inspection, handling, and operation.



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

How does damage tolerance of composites fit within the framework of Constellation requirements?





Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

MSFC-RQMT- 3479 Scope

- Hardware scope.
 - Manned spaceflight hardware including manned launch, retrieval, transport, and landing vehicles, space habitats, and payloads that are launched, retrieved, stored, or operated during any portion of a manned spaceflight mission.
- Materials/structures types.
 - Covered by new standard:
 - Polymer matrix composites.
 - Sandwich construction.
 - Bonded metallics, bonded composites, or bonded metallic-composite.
 - Specifically excluded by new standard:
 - Metal and ceramic matrix composites.
 - Foam.
 - Flexible inflatable structures.
 - Liquid rocket engines.
 - Solid propellants.



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

MSFC- RQMT-3479 Development Approach

- Cast requirements in the framework and language of existing NASA fracture control requirements.
- Review other requirements in addition to NASA ones:
 - Aircraft – Military – Joint Services Specification Guide (JSSG) 2006
 - Aircraft – Civil – FARs/MIL-HDBK-17F
 - General literature
- Address the shortcomings of previous NASA fracture control requirements.
 - Developed requirements with significant input from NASA Fracture Methodology Panel members during 2004 and 2005
- Rely on ANSI/AIAA S-081-2000 for COPVs.
- Refer to MIL-HDBK-17F for specific methodologies.



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Classification of Composite Parts and Bonds for Fracture Control

A part (or bond) is fracture critical if its failure due to the presence of a flaw would result in a catastrophic hazard. All composite parts and bonds shall be classified according to the following:

Exempt

- Non-structural and no safety critical function

Non-Fracture Critical

- Low released mass
- Fail safe
- Contained
- Low risk
- Non-hazardous leak before burst (NHLBB)

Fracture Critical

- Proofed
- Damage tolerant

How does this affect hardware development?



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Implications for Hardware Development

- Damage Threat Assessment (DTA)

Different tasks are performed depending on fracture control classification

- Task 1: Identify the source and type of impact damage that poses a credible threat to the hardware
- Task 2: Characterize the impact damage size and energy level to be considered during all types of damage tolerant tests
- Task 3: Generate an as-manufactured initial flaw type and size assessment for the hardware

- Impact Damage Protection Plan (IDPP)

- Plan required for all hardware except exempt, low released mass, and contained
 - Plan addresses each threat identified in DTA
 - Protection method (or monitoring method) must be addressed for each threat identified in DTA
- Mitigates risk of impact damage; does not eliminate risk
 - Credible impact damage, identified in the DTA, must be addressed during damage tolerant tests, even for protected hardware

- Inspections & NDE

- Methods discussed in MIL-HDBK-17; POD information typically not available (no 90/95 standard sizes); special visual & walk-around inspections are included
- Damage used to develop residual strength and life curves must be detectable by some form of inspection



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Implications for Hardware Development

- Damage Tolerance Tests
 - Building Block Approach based on MIL-HDBK-17
 - Coupon Tests
 - Generate a family of life and residual strength curves with damage in appropriate environment
 - Determine damage configuration and sizes from the DTA (Task 2 & 3) and NDE capability
 - Establish no-growth threshold strain for low risk parts
 - Support analysis and design to assure success of full-scale tests
 - Development Tests
 - Evaluate structural elements representative of flight design
 - Demonstrate residual strength and life capability for the design spectrum with damage
 - Assist in any anomaly resolution & guide the design toward successful full-scale tests
 - Full-Scale Component Tests
 - Verify full-scale flight-like components with induced damage sites
 - Demonstrate the ability of the structure to sustain design loads for 1 lifetime, including a load enhancement factor (LEF), and a subsequent design ultimate load (DUL) with no damage growth or initiation
 - Demonstrate the ability of the structure to sustain design loads for 4 lifetimes, including an LEF, and a subsequent design limit load (DLL) with no damage initiation and no structural failure



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Implications for Hardware Development

- Analysis
 - Primary purpose is to assist in assuring a successful full-scale damage tolerance test
 - Potential methods
 - Strength assessment with residual strength allowables
 - Advanced methods such as the virtual crack closure technique (VCCT)
 - Future updates to MIL-HDBK-17
- Data
 - Statistical basis
 - A-Basis (99/95) for Ultimate Strength per MIL-HDBK-17
 - Load Enhancement Factor (LEF) per MIL-HDBK-17
 - LEF for fatigue spectrum sufficient to establish A-Basis reliability on life
 - Requires Weibull shape parameters for residual strength and fatigue life tests
 - Damage tolerance coupon tests
 - Sufficient number to develop Weibull shape parameters
 - Sufficient number to encompass DTA and NDE damage sizes
 - Impact testing
 - Sufficient number to develop impact energy, size, and configuration curves



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

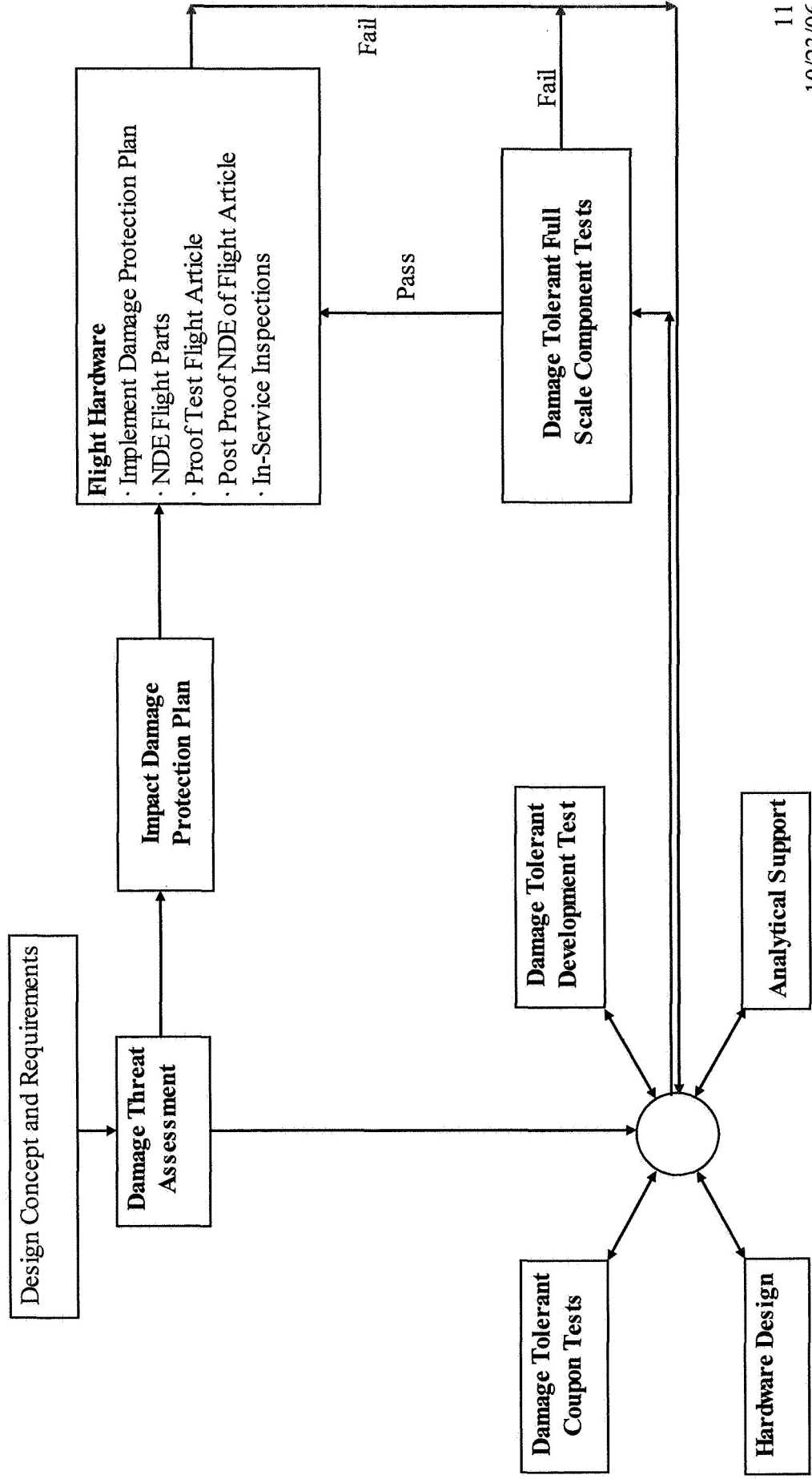
Examples of MSFC-RQMT-3479 Criteria



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Steps in Establishing Damage Tolerance

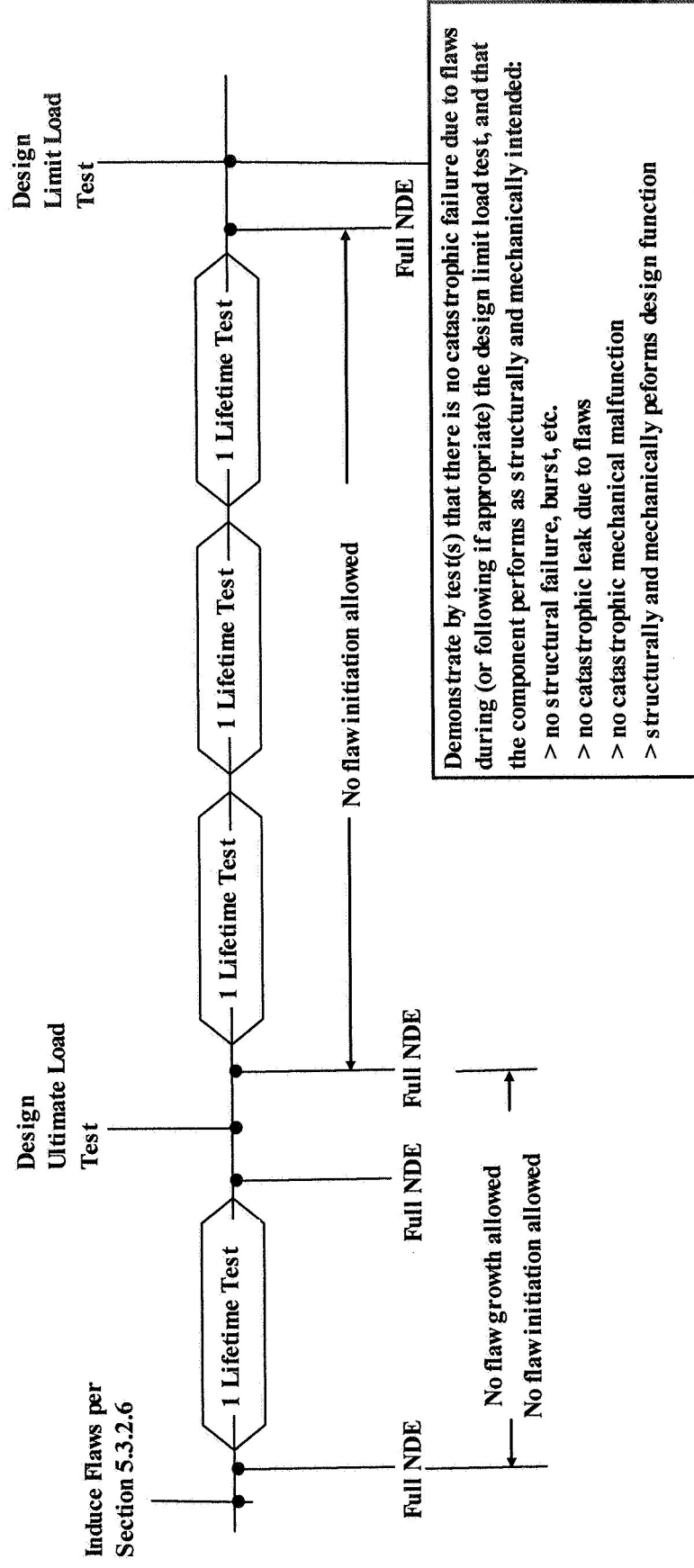




Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Damage Tolerant Full-Scale Component Test





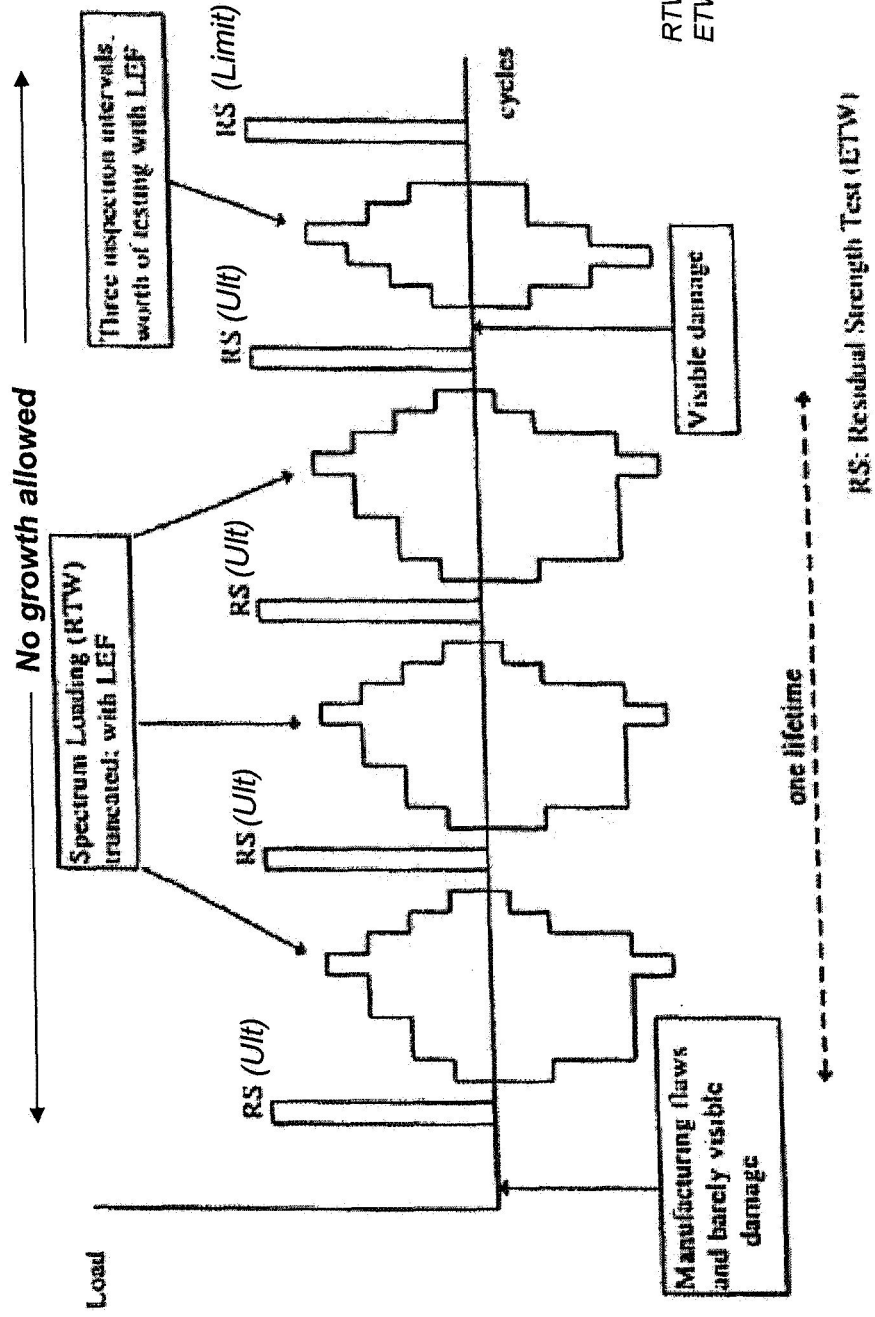
Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Application/ Examples -MIL-HDBK-17-3F – Figure 7.9.1.6

Rotocraft (Sikorsky)

Damage Tolerant Certification Procedure Schematic





Composites Damage Tolerance Workshop

MS&C Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

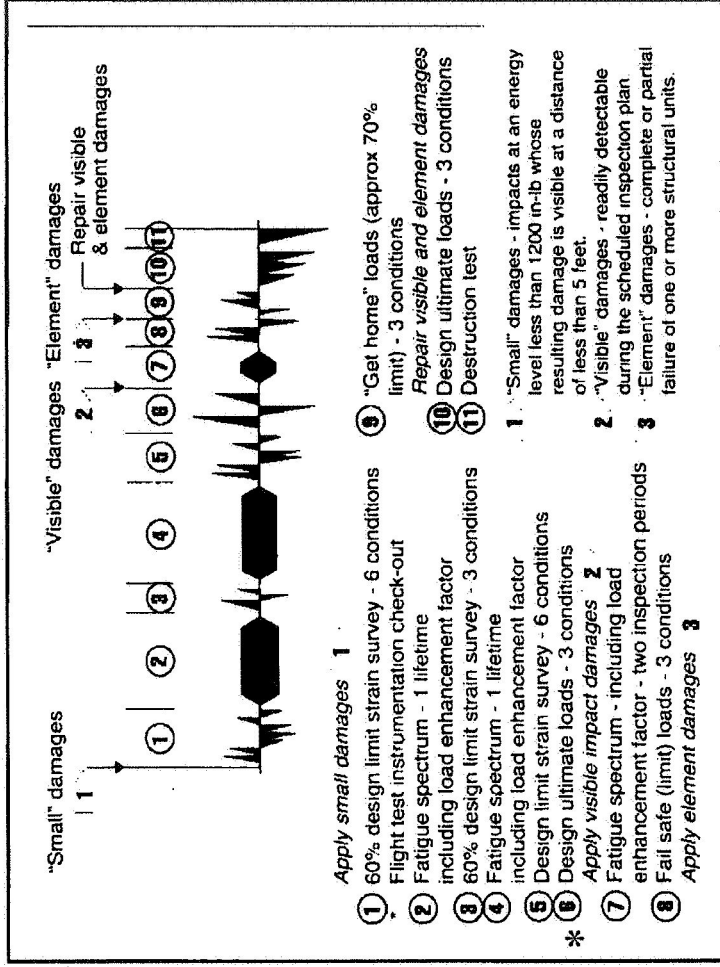
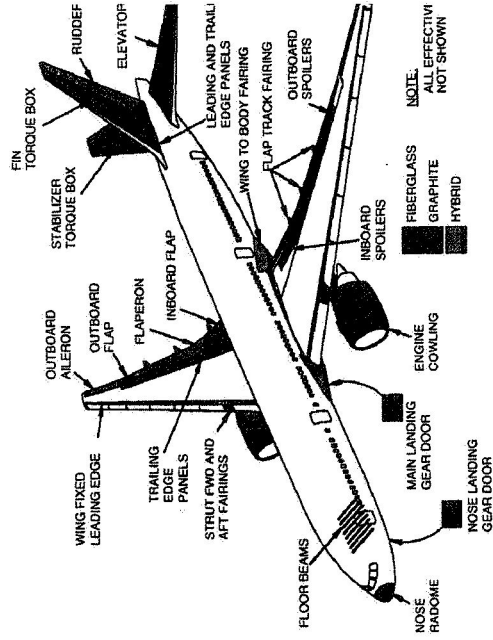
Application/ Examples -MIL-HDBK-17-3F – Section 7.9.2

Commercial Aircraft – Boeing 777 Empennage Torque Boxes

Preproduction Horizontal Stabilizer Test Sequence – Demonstrate “No Growth”

Boeing 777 – Composite Usage

- Empennage Torque Boxes
- Passenger Floor Beams
- Aero Fairings and Other Secondary Structures





Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Summary Sheet - Composite Fracture Control Classifications and Requirements

Requirements	Non-Fracture Critical						Fracture Critical	
	Low Released Mass	Fail Safe	Contained			Proof Tested	Damage Tolerant	
			Metallic Enclosure	Composite Enclosure	LowRisk			
Reference Section	5.2.1	5.2.2	5.2.3.A	5.2.3.B	5.2.4	5.2.5	5.3.1	5.3.2
No catastrophic hazard/loss of SCF	x	x	x	x		x		
Part must be larger than open holes			x	x				
Enclosure/container not FC				x		x		
Not a pressure vessel					x	x		
No hazardous fluid					x	x		
FOS on containment			1.0 Fty, analysis or test	1.15 p/tratn test, or 1.15 p/tratn anlysis s/b test				
				w/impact damage > NDE, from loose part, DTA, or imposed - verf by test	w/impact damage > NDE, DTA, or imposed - verf by test	at Ult FOS x MDP w/impact damage > NDE, DTA, or imposed - verf by test		Per Fig. 5
DUL capability	NFC impacted parts - verf by test							
Inspections								
1. Visual								between each flight
a. Walkaround								pre and post proof, and after every 3 rd flight
b. Special Visual		pre and post proof, and between flights		pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof, and between flights	pre and post proof	pre and post proof
2. NDE		pre and post proof		pre and post proof	pre and post proof	1.2 x limit, initially and between flights		Initially, 1.05 min x limit
Proof tested (< 80% Ult) ¹	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	Foot Note 1	x	x
DTATask 1		x		x	x	x ²	x	x
DTATask 2				x ²	x ^{2.3}			x
DTATask 3					x ³			x
IDPP		x		x	x	x	x	x



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Summary Sheet - Composite Fracture Control Classifications and Requirements

Requirements	Non-Fracture Critical					Fracture Critical	
	Low Released Mass	Fail Safe	Metallic Enclosure	Composite Enclosure	Low Risk	NHLBB	Proof Tested
Reference Section	5.2.1	5.2.2	5.2.3.A	5.2.3.B	5.2.4	5.2.5	5.3.1
Damage tolerant coupon tests					χ^2		
Damage tolerant development tests							
Damage tolerant full-scale component tests	FC impacted parts	FC impacted parts					
Traceability (Section 6.4)		x		x	x	x	x
Unique Requirements							
Pressurized enclosures shall have the characteristic of being NHLBB				x			
Walls shall leak \leq MDP, Verf. by test						for TTF 10 t or 1 inch	
Wall shall not burst @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch	
Flaw shall not grow @ Ult x MDP, Verf. By test						for TTF 10 t or 1 inch	
No depressurization as pressure leaks down						x	
Generally limited to payloads							x
Internal to payload vehicle, module	x		implied	implied			
Debris shall meet low mass		x					
Below no-growth threshold strain					x		
Remaining struc analytically assessed at 1.15 x redistributed dyn load		x - analytical meth verified by test					
Remaining impacted struc must support 1.15 x redistributed limit load		x - NFC parts - verf by test					
See also 5003 for Shuttle payload	x						
No HERM, HMRM, hab mod, SPF bond					x		

Foot Notes:

1. NASA-STD-5001 requires proof test of all composite parts/structures to 1.05/1.20.
2. Required to the extent needed to establish impact damage size for DUL capability test (Line 11).
3. Required to the extent needed to determine no-growth threshold strain (Line 35).



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

BACKUP

Example of Technical Issue Investigated during Development of MSFC-RQMT-3479



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

No-growth Threshold Strain

- The no-growth threshold strain is the strain level below which flaws of interest do not grow in 10^6 (10^8 for rotating hardware) cycles at the applicable load ratio.
- The no-growth threshold strain is established by test.
- This strain is needed for the low risk classification or in the truncation of tests spectra.
- The issue was:
 - Can we specify a default value, say “some” percent of ultimate strength that would be applicable for all situations and avoid testing to establish the no-growth threshold strain?



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Review of the Literature

- Threshold strains not addressed in ASTM standards.
- Literature confusing, can be misleading and easily misunderstood.
- “Threshold” may refer to undamaged state as in “endurance limit”.
- Thresholds are sometimes addressed as percent of static undamaged strength and sometimes as percent of strength after damage. Also addressed as a percent of the critical strain energy release rate.
- Strain range (R) is important as well as strain magnitude.
- Numbers quoted as thresholds are generally application specific.
- Look at a specific case to gain some insight:
 - Han, H. T., Mitrovic, M., and Turkgenç, O., “The effects of Loading Parameters on Fatigue of Composite Laminates: Part III”, DOT/FAA/AR-99/22, June 1999.



Composites Damage Tolerance Workshop

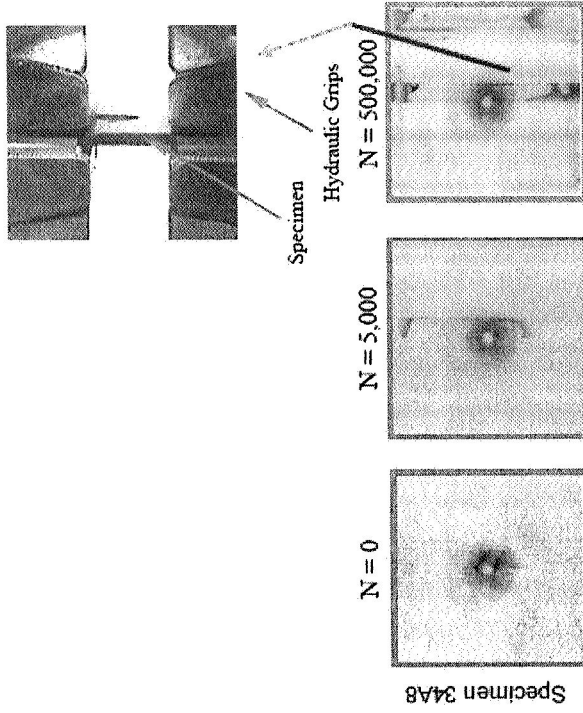
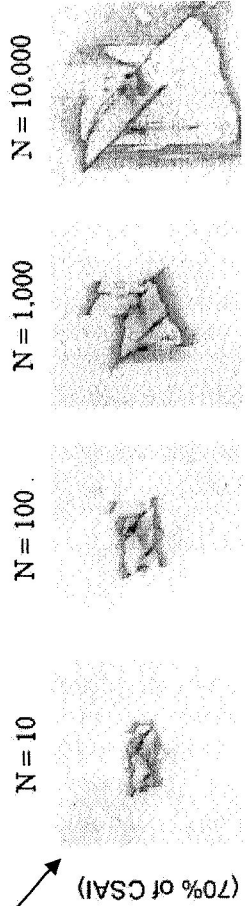
MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Constant Amplitude Loading

Constant-Amplitude Compression-Compression (R = ∞)				
Specimen Number	Load Level [% of CSAI]	Number of Cycles	Impact-Induced Damage Growth	
32A6	40%	1,000,000	no	
32A7	40%	1,000,000	no	
31C7	40%	1,000,000	no	
33B1	50%	1,000,000	no	
31D4	50%	1,000,000	no	
33B4	50%	1,000,000	no	
31E5	60%	1,000,000	no	
34A8	60%	>500,000	yes	
31D3	60%	1,000,000	no	
33B2	70%	141,607*	yes	
31F2	70%	>10,000**	yes	
35A6	70%	>100,000	yes	
33F3	80%	136*	yes	
31E1	80%	587*	yes	
33C3	80%	>1,000	yes	

* indicates cycles to final failure

** indicates number of cycles that causes propagation of delamination to the tab region



- At 70% load level, always get growth.

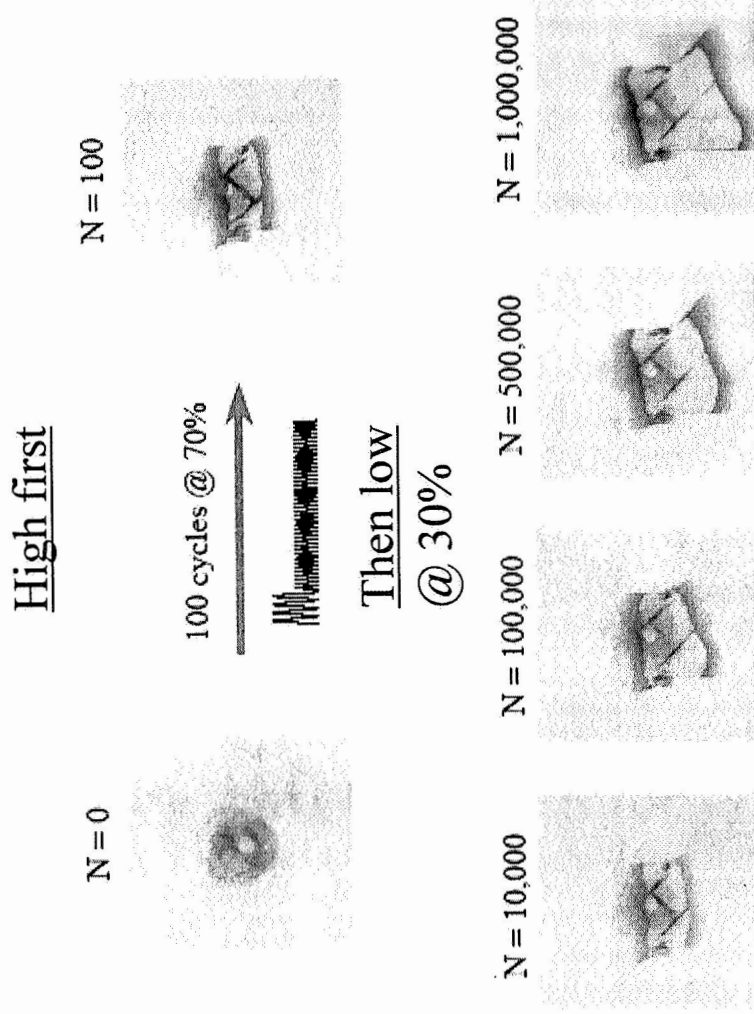
No-growth at 60% CSAI is misleading.



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Spectrum Loading - High/Low



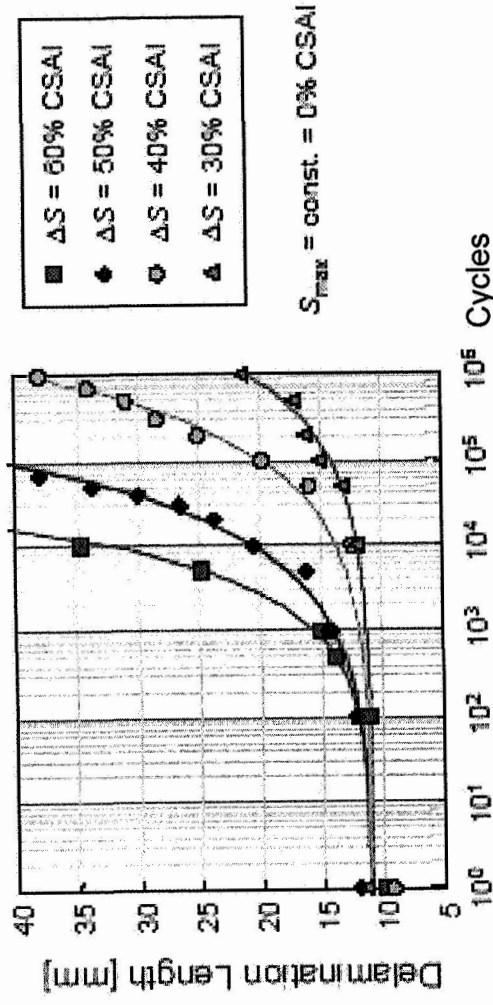
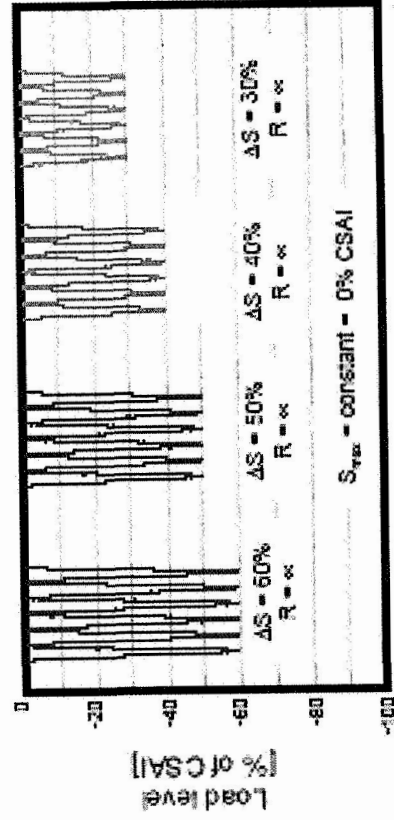
Note growth at 30% CSAL, 2nd block



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

Spectrum Loading - High/Low - 2nd Block Growth



Load Cases

Constant maximum load,

variable load range

- S_{\max} = constant = 0% CSAI

- ΔS = 30, 40, 50, 60% CSAI

Note growth at 30% CSAI



Composites Damage Tolerance Workshop

MSFC Engineering Directorate
Damage Tolerance Assessment Branch
Damage Tolerance Team/W. Gregg

No-Growth Threshold Issue Example Conclusion and Recommendation

- Data exist that show flaw growth can occur at cyclic loads that are quite low ($< 30\%$ CSAI), whereas other data show quite high loads are required to initiate flaw growth.
- Thresholds discussed in the literature are application specific.
- Specifying a generic threshold lets the developers off the hook for understanding their hardware and its application.
- Not comfortable with choosing a single number for all applications.
- Recommendation:
 - Require developers who need a threshold value to generate one by test.
 - Allow use of existing data if verified by tests for current application.